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**ACOUSTICS OF THE SAGRADA FAMÍLIA CHURCH AND THE GAUDÍ'S
BELLS: JOINT RESEARCH BETWEEN POLYTECHNICAL UNIVERSITY
OF CATALUNYA AND KYUSHU UNIVERSITY**

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Abstract

A Catalan architect, Antoni Gaudí (1852-1926) seems to have envisaged the Sagrada Família as a gigantic musical instrument. Each tower seems to be designed as a belfry, in which many tubular bells will be installed. Its upper section of the Nativity Façade has numerous windows with characteristic louvers. The lower section is almost closed and connected to the nave through muffler-like structures. Therefore, Gaudí's bell music is to be propagated to the nave through the internal passage as well as to be radiated to the exterior space. Acoustic radiation from the windows and propagation through the lower structures are simulated by two-dimensional FDTD (Finite-Difference Time-Domain) method. The window yields a broad directivity pattern in lower frequencies (63 Hz – 250 Hz) and a beam pattern in higher frequencies (500 Hz – 2 kHz). A beam pattern consisting of several sharp lobes is similar to that formed by a linear array consisting of several point sources. In Gaudí's windows, both edges of the louvers and the gaps between the louvers yield secondary sources for the beam-like radiation. Six receiving points along a 1/25-scaled model of the lower structure indicate interactions between the direct sound from the top of the lower section and the reflection from the floor. Also, an impulse-response measurement on this model suggests that an attenuation of 40 dB is estimated above 100 Hz and that the frequencies below 110 Hz are strongly cut off. This cutoff frequency can be estimated from the baffled-piston radiation. In addition, numerical simulations exhibit that the curved ceiling in cylindrical rooms can serve to reduce the reverberation time but cannot yield a stronger attenuation. The vibrational and radiational characteristics of a miniature bell similar to a Gaudí's tubular bell are investigated by the FE (Finite-Element) method and the acoustic measurement in an anechoic room. The measured radiational pattern indicates a good agreement with the simulated result.

INTRODUCTION

The construction of the Sagrada Família Church began in 1882. Gaudí was commissioned with the direction of the work in 1883 shortly after the resignation of the architect Francesc de P. Villar. However, Gaudí died by traffic accident in 1926 at the first stage of the huge Sagrada Família Project. In 1936 the Civil War destroyed the Gaudí's studio and workshop, from which Gaudí's original materials were lost.

Nevertheless, the construction is still going on. It is thus important for the present and future generations to look for Gaudí's original intention based on the surviving things and matters as well as to create new ideas and incorporate them into the construction.

According to the ground plan of the Sagrada Família [Bonet, 2000; Campos, 2002], three facades (the Nativity, the Passion, and the Glory Façade) are to be constructed facing to the east, west, and south, respectively. Each Façade consists of the four bell towers. The height of the longest tower exceeds 100 meters. The Nativity Façade was almost completed by Gaudí himself, and the Passion Façade was completed by the next-generation architects. The Glory façade has not been completed yet. The altar faces the north. Furthermore, six main towers will rise over the central nave, which is surrounded by the side aisles. The 12 towers rising from the three facades are the belfries. It is said that Gaudí planned to install many bells and transmit bell music to the city of Barcelona. In fact, Gaudí carried out the propagation experiment using a model bell in 1914. His acoustical image and concept can be inferred from **Figs. 1** and **2** [Campos, 2002]. Also, it is designed to lead this bell music to the central nave in the Sagrada família. Although the model bell that was used at the propagation experiment still remains, it is doubtful if the shape of this tubular bell (an almost straight tube plus a triangular-like enlarging frange at the end) is the final image of Gaudí's tubular bell.

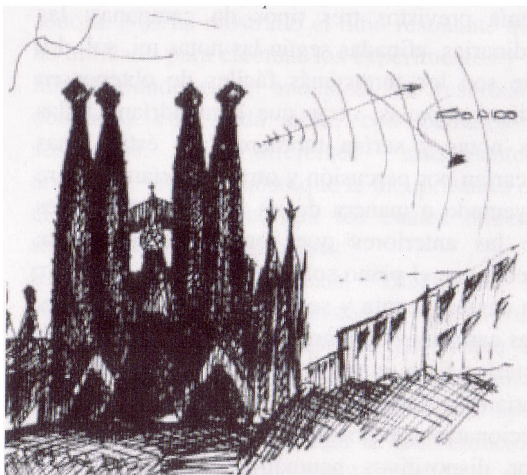


Fig. 1. Image of sound radiation from the Sagrada Família belfries [Campos, 2002].

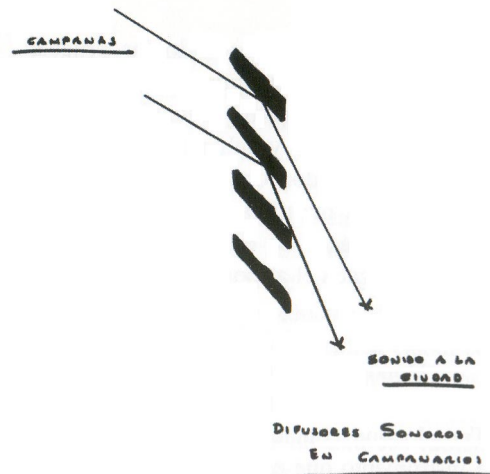


Fig. 2. Image of bell sound transmission through the louvered windows [Campos, 2002].

Since there seemed to be a lot of interesting topics on the acoustical aspects of the Sagrada Família, a framework agreement for the research collaboration was concluded in June of 2003 between the three: The Polytechnical University of Catalunya (Depts. of Architectural Presentation-I, Architectural Technology-I, and Mechanical Engineering), the Kyushu University (Faculty of Design, formerly the Kyushu Institute of Design), and the Gaudí Club Cultural Association (Barcelona). However, the research object is very huge and complicated, in addition Gaudí's original material has been lost. Nevertheless, our collaboration has been managed with mutual research interests. Although this paper describes most results yielded during the first stage at the Kyushu University, various informative supports provided from the UPC and the Gaudí Club as well as mutual discussions are involved.

BASIC STRUCTURE OF THE NATIVITY FAÇADE

The Façade of Nativity, which was constructed by Gaudí, is divided into two both horizontally and vertically. **Figure 3** depicts the cross-sectional view. The Façade is vertically divided at the central surface passing through the choir loft. That is, the Façade has twin-tower structure. We thus consider the left half. Also, the Façade may be horizontally divided into the upper and the lower structure. The upper structure, which is enclosed by a blue rectangle in Fig. 3, has many windows with characteristic louvers. The bell sound is radiated from these windows. The lower structure, which is enclosed by a red rectangle, consists of many cylindrical rooms through which the bell sound is conveyed to the nave. The cylindrical rooms, which have very few windows, are connected vertically and horizontally. Particularly, the vertical connection is done with a short cylindrical neck. This kind of passage made of constrictions and enlargements might function as an acoustic filter or an acoustic attenuator (silencer) [Kinsler et al., 2000].

Also, the choir loft is constructed at the height of about 30 meters. Therefore, we may assume that Gaudí envisaged the music of bells and chant in the central nave. In other word, the Sagrada Família was considered as a kind of huge musical instruments, whose music was to be heard both outside and inside. The objective of this paper is to examine the acoustical properties of the belfries and bells based on numerical simulations and model experiments on the radiation and propagation.

Specifically speaking, acoustic radiation from the windows in the upper section enclosed by a blue rectangle (see Fig. 3) and acoustic propagation through the uppermost cylinders in the lower section enclosed by a red rectangle will be considered by introducing many simplifications. The geometries of the interested sections are determined from a reference book [Tanaka, 1987], where the detailed structures and configurations of the windows and cylindrical passages are drawn. However, since it is difficult to assume the installation of the bells, only a model bell is considered.

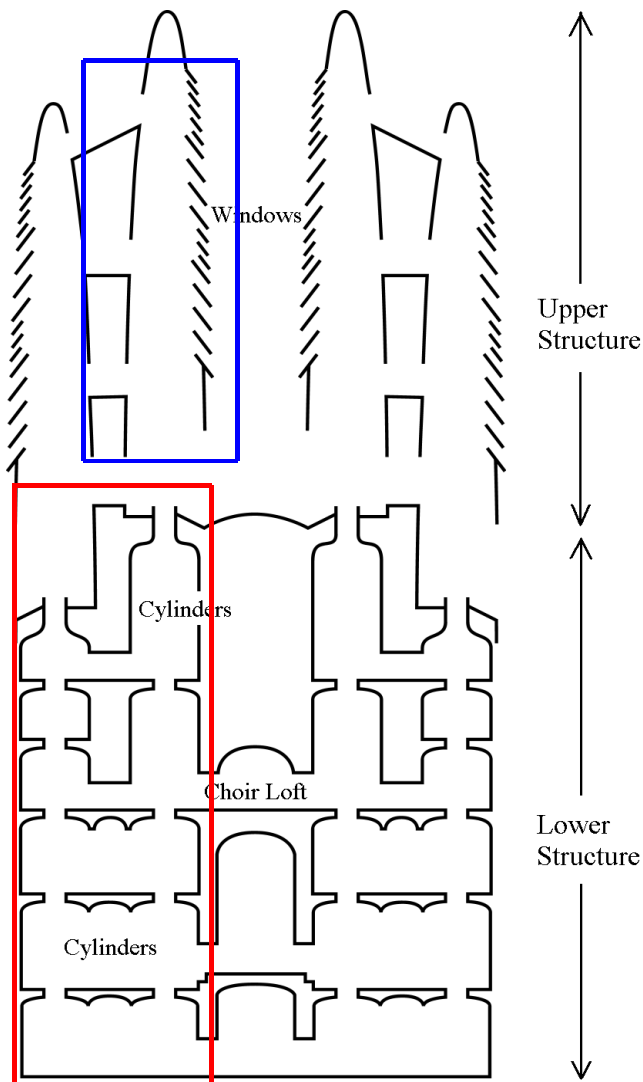


Fig. 3. Cross section of the Nativity Façade. The sections enclosed by a blue rectangle and a red rectangle are the present reserach objects.

ACOUSTIC RADIATION FROM THE LOUVERED WINDOWS

Basic structure of the belfry windows

The belfry windows are shown in **Fig. 4** (a) and the window section enclosed by a blue rectangle in Fig. 3 is illustrated in Fig. 4 (b) [Tanaka, 1987]. Basically, this window section consists of two types. Type A is made of four to six smaller windows with louvers and is arranged along the inner spiral stairs. Type B is made of three or four larger windows with louvers. Such an arrangement of Types A and B is rotating up along the parabolic tower in the interval of about 30 degrees. Also, the louver has a slant angle of about 45 degrees, and we may expect the downward radiation of the bell sound as depicted in Fig. 2. Moreover, the louver surface is not flat but corrugated, showing Gaudí's characteristic design. This corrugation might bring any acoustical effect to the radiation.

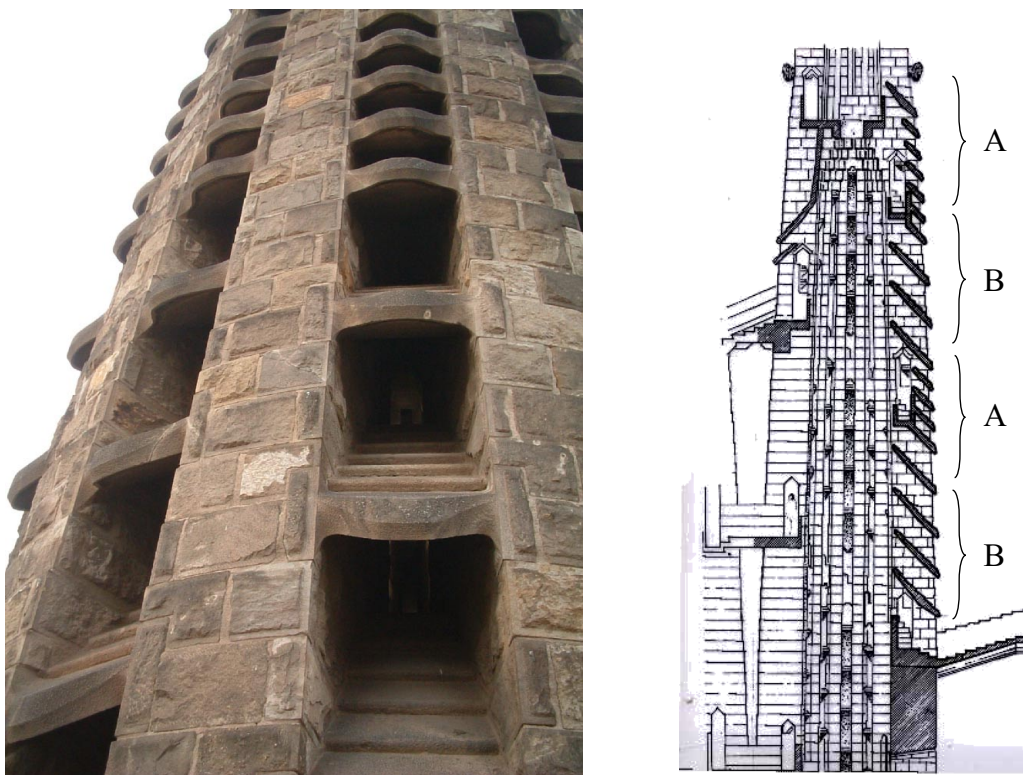


Fig. 4. The bell tower windows. (a): A photo showing the windows with slant louvers; (b): Cross-sectional view of the window section in Fig. 3 [Tanaka, 1987].

Numerical simulations using FDTD method

The 2-D (two-dimensional) FDTD (Finite-Difference Time-Domain) method [Suzuki et al., 2007; Botteldooren, 1994] is applied to our numerical calculation. This FDTD method is more suitable for the visualization than the FE (Finite-Element) and BE (Boundary-Element) methods. The acoustic pressure and the particle velocities (in x and y directions) are discretized by placing a Staggered-Grid mesh. The equations of motion and the equation of continuity are expressed by the finite-difference scheme.

Specifically, the Matlab source code in 2-D FD equations is created but it is omitted here for saving the space (cf. [Suzuki et al., 2007]).

Computational assumptions and conditions

Since it is difficult to analyse a series of windows shown in Fig. 4, only Type A or Type B is treated separately as depicted in Fig. 5. For example, Type A is put in the region for computation as indicated in Fig. 6, which has the area of $14 \text{ m} \times 14 \text{ m}$, and the radiated sound pressure level is computed in the meshed area ($10 \text{ m} \times 5 \text{ m}$) in steps of $0.5 \text{ m} \times 0.5 \text{ m}$. The edges of the right-half area are guarded by a quasi-reflection-free layer [Yokota et al., 2002]. The grid widths in the x and y directions are respectively given as $\Delta x = 0.01 \text{ m}$ and $\Delta y = 0.01 \text{ m}$. The sampling time is given by $\Delta t = \Delta x / 1.5c = 19.6 \mu\text{s}$, where c denotes the sound speed. This Δt satisfies the stability condition.

The sound source p_{IN} is simplified as the following Gaussian pulse: $p_{\text{IN}} = \exp\{ - [(t - 30\Delta t)/(8\Delta t)]^2 \}$. The frequency characteristic of this pulse is almost flat up to 3 kHz. The symbols O_1 , O_2 , and O_3 in Fig. 6 denote the assumed source positions. Also, the wall is assumed upside and downside the window as shown in Figs. 5 and 6. Acoustic impedance of the normal incidence to the wall surface is assumed to be 50 times the air impedance. This wall impedance corresponds to the reflection coefficient of about 0.96 when defined by the acoustic pressure. The magnitude of the corrugation (凹凸) made on the actual louver surface is about 0.3 to 0.5 meters.

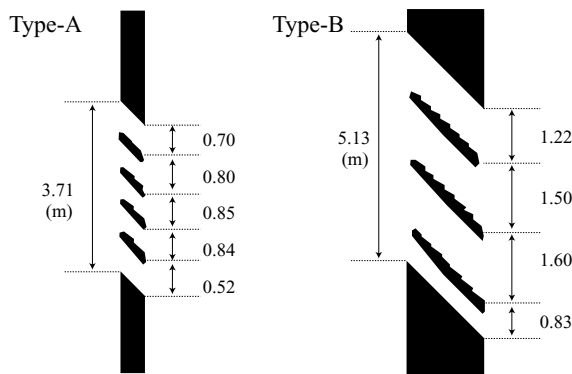


Fig. 5. Geometry of the separated windows used for simulations [Tanaka, 1987].

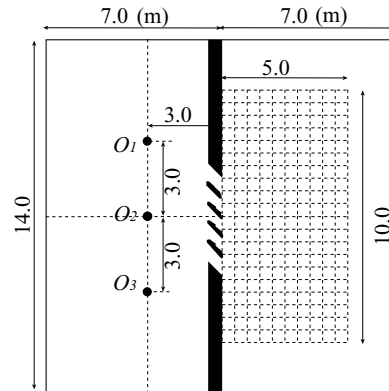


Fig. 6. Point-source position (O_1 , O_2 , or O_3) and calculation area (meshed).

Simulations of sound propagation to the exterior

The acoustic propagation is visualized in Figs. 7 (a) and (b) after the above Gaussian pulse is generated at point O_2 and O_3 (cf. Fig. 6), respectively. The window is Type A with the surface-corrugated louvers. At $t = 10 \text{ ms}$ after the pulse generation, we can clearly see the wave front passing through the space between the louvers in Fig. 7 (a), however, the pulse has just arrived at the lowest louver in Fig. 7 (b). Also, the circular wave fronts of the reflecting waves are very clear, and the sources of these waves are the left-side edges of the louvers. At $t = 15 \text{ ms}$ the situation of sound propagation is already considerably complicated. Observing the wave fronts in detail, we may understand that the passages between the louvers and the right-side edges of the louvers are working as the secondary sources. Since the phase difference between these secondary sources is ambiguous, it may be assumed that several point sources

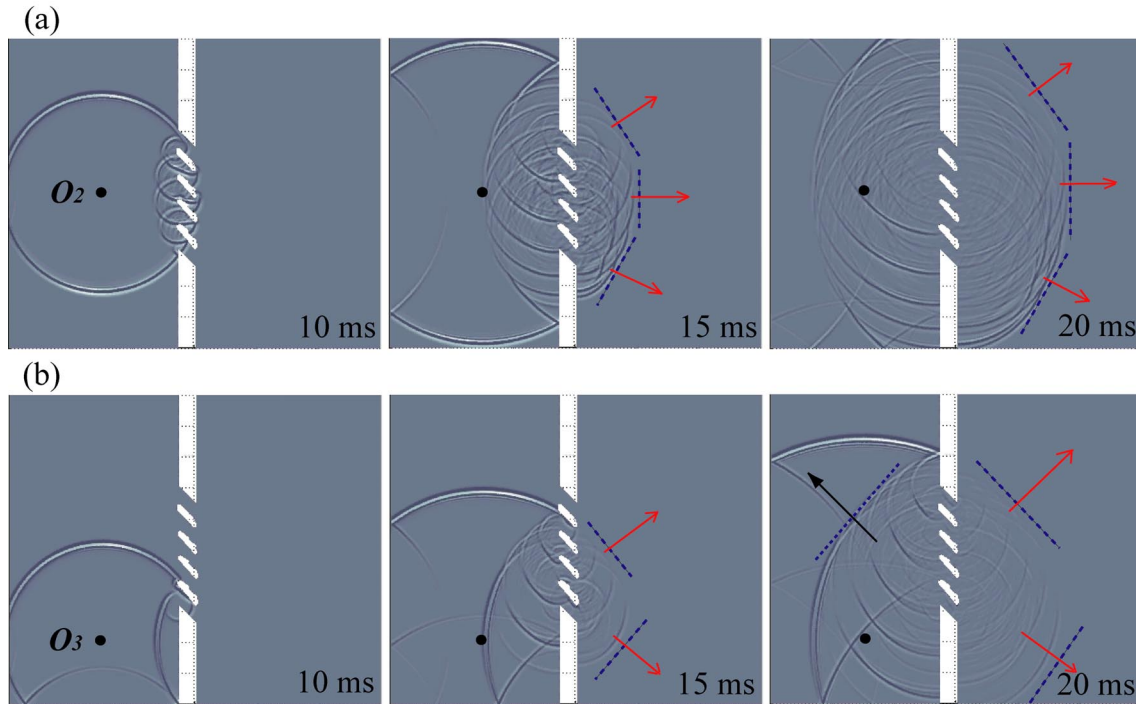


Fig. 7. Sound propagation through the louvered window (Type A with the surface-corrugated louvers). (a): pulse source at O_2 ; (b) pulse source at O_3 .

with the opposite phases are formed at the window in an average sense. It might be considered that a kind of linear array is formed along the louvered window. As a result, the sound propagates toward almost all directions as shown in (a) at the frame of $t = 20$ ms. On the other hand, when the source lies at O_3 , sound propagation is roughly divided into two directions as depicted in (b). Particularly, we have to notice that a relatively large energy is propagated into the upward direction. Also, a strong reflection toward the interior space is observed in (b) compared with (a). We can thus recognize that both edges of the louvers form the secondary sources for the outward radiation and for the inward reflection, respectively. The upward and downward propagations are a little retarded than the frontal propagation in (a), and thus the reflections between the louvers are suggested (see **Fig. 8**). When the pulse source is located at O_1 , the image illustrated in Fig. 2 is applicable.

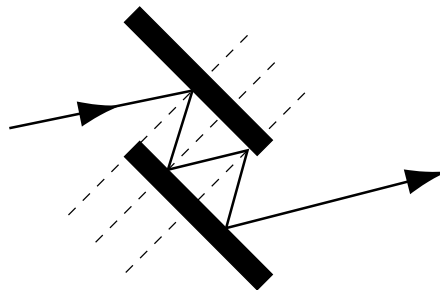


Fig. 8. Schematic on the multiple reflections between the louvers. Such multiple reflections cause the upward radiation.

Frequency dependence of the radiation directivity

The frequency dependence of the acoustic radiation is illustrated in **Fig. 9** when the Gaussian pulse is generated at point O_2 or O_3 and the window type is A or B. The responses in 1/3-octave bands whose central frequencies are 63, 125, 250, 500, 1000, 2000 Hz,

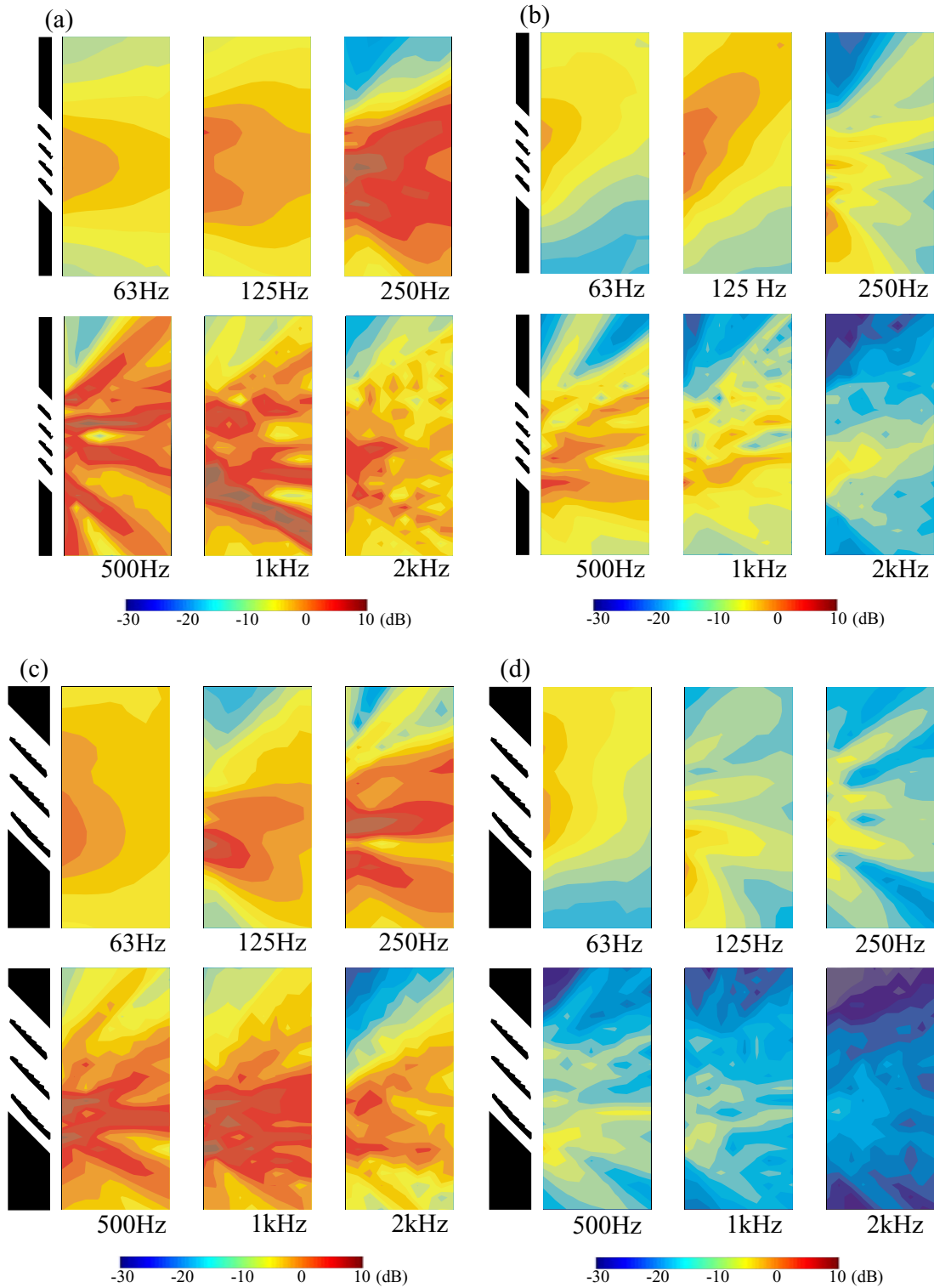


Fig. 9. Frequency dependence of acoustic radiation field. (a): window type A with louver corrugations, source O_2 ; (b): type A, O_3 ; (c) type B, O_2 ; (d): type B, O_3 .

and 2000 Hz are demonstrated. When the sound source lies at O_2 , relatively similar radiation patterns are shown regardless of the window type [cf. Figs. 9 (a) and (c)]. On the other hand, when the source lies at O_3 , the radiation pattern depends on the window type as well known from the 125-Hz frames in (b) and (d). These radiation directivity patterns can be inferred from the impulse response patterns illustrated in Fig. 7. Particularly, it should be noted that the upward radiation is stressed in (b) except the 250-Hz frame. Also, the pressure level is very low in (d) except the 63-Hz frame. Summing up, the lower source position O_3 relative to the window center is inappropriate to propagate the bell sounds to the people on the ground (cf. Fig. 8).

Roughly speaking, broad directivity patterns are indicated in 63, 125, and 250 Hz. The wavelength of the 125-Hz component is 2.7 m, and the window lengths are 3.7 m and 5.1 m. Thus, the radiation directivity is not sharp in these lower frequencies. However, at 500 Hz a beam-like directivity pattern is indicated. There seem to be five beams. Also, at 2 kHz many speckles due to the interference are recognized, particularly in (a). These radiation characteristics in higher frequencies (0.5 – 2.0 kHz) may be interpreted as the results of so-called “line array” formed along the window. The number of (secondary) sources arranged along this linear array can be varied according to the frequency and the louver interval.

Comparing the results on the louvers with and without the surface corrugation, we know that there is no appreciable difference in the directivity pattern below 2 kHz, although the sound pressure level in the case of the louvers with the corrugation is reduced by a few dBs only in higher frequencies. See Ref [Nishimoto and Yoshikawa, 2006] for more detailed information and discussion.

SOUND PROPAGATION THROUGH THE BELFRY LOWER STRUCTURE

Measurement on a 1/25-scaled model of the lower structure

According to Gaudí's plans that were actually measured by Dr. Hiroya Tanaka of the Gaudí Club Cultural Association in Barcelona, a simplified 1/25-scaled model of the lower structure was made of acrylic resin (Plexiglas). This model corresponds to the section enclosed by a red rectangle shown in Fig. 3. The details in structure are simplified, but major geometries are correct. **Figure 10** shows (a) a drawing by the computer

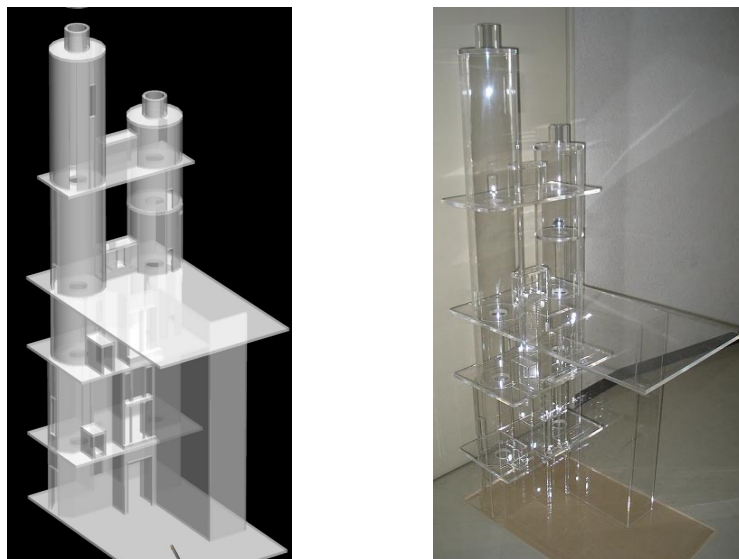


Fig. 10. A 1/25-scaled model of the lower structure. (a): computer graphics; (b): experimental model. Size: $0.5 \times 0.8 \times 1.7$ m. Actual height: about 45 m.

graphics and (b) a photo of the acrylic resin model. It is well demonstrated that the lower structure consists of five or six rooms, which are vertically connected by short cylindrical necks. Moreover, each room has a few small openings. The openings in lower rooms may collect the bell sound and radiate it toward the nave space. In this section attenuation effects of the lower structure are examined experimentally. However, we have no intention to carry out the scaled-model experiment in its rigorous meaning.

Since our experimental model was scaled in $1/25$, acoustical measurement was carried out in low- and high-frequency ranges using different speaker systems. According to the frequency characteristics of the measuring systems, the measurement was feasible in a lower frequency range of 500 Hz to 17.5 kHz (20 Hz to 700 Hz in actual scale) and in a higher frequency range of 15 kHz to 50 kHz (600 Hz to 2 kHz in actual scale). The result measured in the lower frequency range is illustrated in **Fig. 11**. The speaker is set up on the top of the lower tower (the outward tower when the belfries are seen from the outside, cf. Fig. 3). A TSP (Time-Stretched Pulse) signal is used as the input signal. The sampling frequency is 48 kHz and the DFT points are 2^{16} . Alphabets “a” to “k” shown in Fig. 11 denote the measurement points in the model.

The measurement result of Fig. 11 shows relatively flat frequency characteristic when the frequency higher than about 100 Hz is considered. If an octave band of the centre frequency 1 kHz is examined, the acoustic pressure received at point “f” is weaker than that at point “a” by 37 dB. The response in the higher frequency range (600 Hz to 2 kHz in actual scale) indicates similar flat attenuation, which can be attributed to the diffusive-like field formed in large rooms. Since the speaker is not omnidirectional, this level difference of 37 dB should be corrected and we may possibly expect the attenuation of over 40 dB between 100 Hz and 2 kHz. The attenuation level at each point in Fig. 11 is also calculated by considering the lower structure as the coupling rooms on the hypothesis of the diffusive field. The result (not shown here) confirms an increase in the attenuation level. Spectral attenuation of about 40 dB between about 100 Hz and about 2 kHz seems to be a reasonable result.

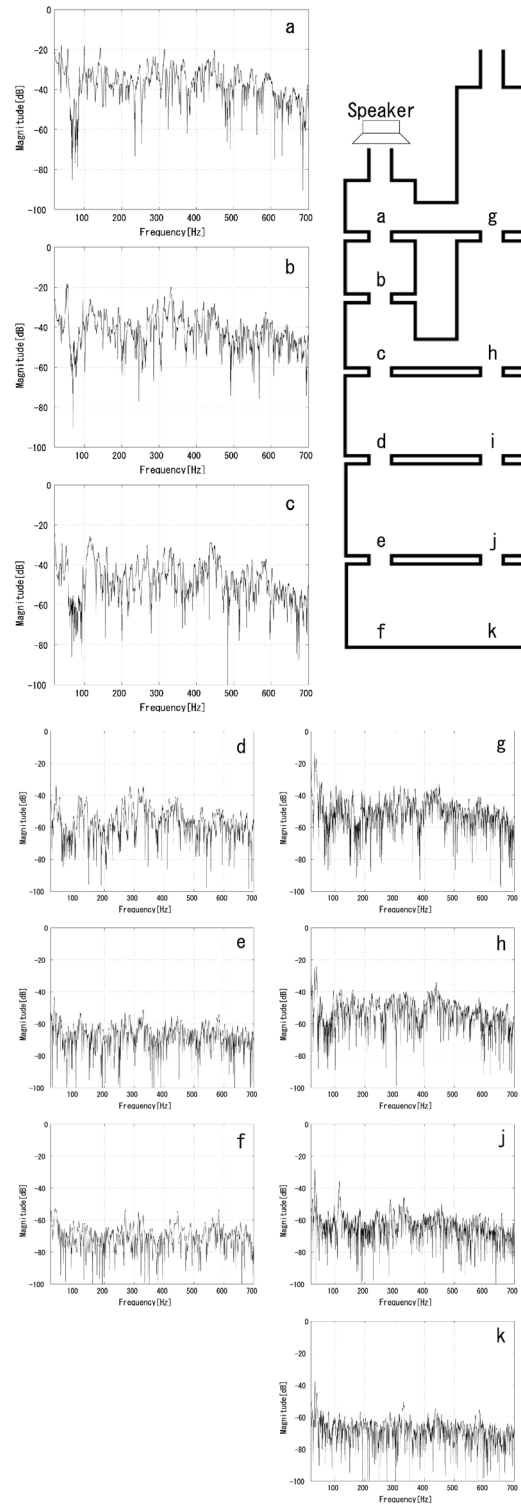


Fig. 11. Sound propagation through the lower structure model (0 – 700 Hz).

Low-frequency cutoff

On the other hand, the frequency response is strongly cut off below about 100 Hz as clearly shown in the data of points “a”, “b”, and “c” in Fig. 11. A series of the enlargement and constriction in cross section can be considered as the acoustic low-pass filter [Kinsler et al., 2000], but it is correct only if the change in cross section is small. In Fig. 11 the left, top room consists of an opening neck of diameter 1.5 m and a cylinder of diameter 4 m. We may thus assume the situation that the sound is radiated from a vibrating piston surrounded by an infinite baffle. Low-frequency radiation is very weak in this configuration as estimated from the radiation impedance. As a result the cutoff frequency is estimated by “wavelength = 2 × diameter” and is then approximately given as $f_{\text{cutoff}} = 110$ Hz. This theoretical result seems to support the validity of the measured result.

However, it should be noted there are sharp responses below 50 Hz as shown in “a” to “c” in Fig. 11. Although these responses might be due to the Helmholtz resonance, the calculated result does not well agree with the measured result. Anyway, the frequency components below about 100 Hz are strongly attenuated (cf. “a” and “f” in Fig. 11). Therefore, it may be concluded that bell sounds below 100 Hz will not be well heard in the central nave of the Sagrada Familia Church.

Numerical simulations by 2-D FDTD method

Since the height of the upper structure is about 40 m, the bell sound can be propagated to the opening of room “a” as the plane wave in the first approximation. Although the data are not shown here, the following results are obtained:

- (1) The impulse responses suggest the significant influence of the reflection at the floor.
- (2) The low-frequency cutoff is seen near 200 Hz. The discrepancy with the experimental value (100 Hz) may be due to the 2-D assumption for the simulation.
- (3) The attenuation between 200 Hz and 2 kHz is about 20 dB in average. This very low attenuation may be also due to the 2-D assumption.

Furthermore, the effects of the curved ceiling seen in actual structure are simulated by comparing with the flat ceiling. The reverberation time of a room with a curved ceiling is 0.35 s and that of a room with flat ceiling is 0.42 s. This is possibly because the curved ceiling can diverge the wave direction. Such a reduction of the reverberation time might be desirable to hear bell music in the nave. However, simulations on the curved ceiling in the configuration of Fig. 11 do not indicate any appreciable difference in the attenuation characteristics. See Refs. [Narita and Yoshikawa, 2005] and [Yoshikawa and Narita, 2004] for more detailed discussions.

ACOUSTIC RADIATION CHARACTERISTICS OF GAUDÍ’S BELLS

It is not exactly known what bells Gaudí envisaged. The shape of the tubular bell used for the propagation experiment in 1914 does not seem to be his final design. Gaudí would adopt a parabolic or hyperbolic envelope as his tubular bells. For example, one of the Catalan musical instruments, the gralla (double-reed woodwind) has the Gaudí-like geometry as shown in Fig. 12 [Tanaka, 2004]. Probably Gaudí liked such a musical instrument. Also, miniature bells with the geometry similar to the gralla were designed by Tanaka and made by the Koizumi Factory Inc. a few years ago [Koizumi, 2006]. One of them, which is indicated in Fig. 13, was used for our experiment on the radiation characteristics.

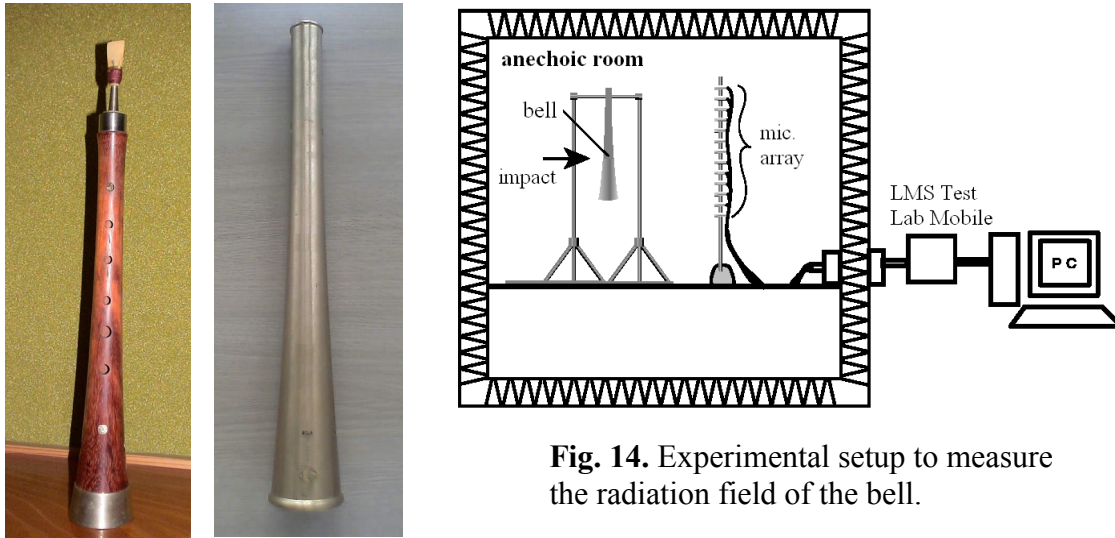


Fig. 14. Experimental setup to measure the radiation field of the bell.

Fig. 12. The gralla. **Fig. 13.** Miniature Gaudí bell.

Experimental setup

Two kinds of microphone array are constructed: a linear array parallel to the bell axis and a semi-circular array surrounding the bell axis at the center. Our experimental setup is shown in **Fig. 14**, where a miniature Gaudí bell (287 mm long, 434 gram) and a linear array (13 microphones are located with an interval of 30 mm and the top one corresponds to the bell top) are arranged in an anechoic room of Kyushu University. The positions of this vertical array, that is, the measurement points are 60, 90, 120, 180, 240, 300, 420, 540, 720, 900, and 1080 mm distant from the bell top edge. A semi-circular array has its radius of 970 mm and 13 microphones are arranged. The measurement is carried out at the height of 127 mm and 237 mm from the bell top and also 37 mm and 200 mm below the bell bottom. The microphone outputs are connected to the lab. PC via the LMS Test Lab Mobile, which amplifies the microphone signals and simultaneously digitize the amplified signals. The bell is struck by an experimenter. The waveforms of the impact magnitude and its frequency characteristic measured by a load cell put on the hammer head are observed to confirm almost the same impact. The impact positions are 77, 142, 162, and 275 mm from the bell top

Experimental results

Only the result on the linear array is demonstrated. The analysis of bell tones gives the peak responses at 483, 1320, 1672, and 2412 Hz. These frequencies correspond to the first to the fourth mode frequencies as estimated below. The radiation patterns measured at these frequencies are shown in **Fig. 15**, where the SPL is plotted and the contour map of equal SPL is drawn. Each frame is interpreted as follows:

- 483 Hz, (2, 0) mode with two nodes along the free-free rod: The radiated pressure is very low near 6 and 21 cm along the bell, and these two points correspond to the nodal points. Three loops are confirmed near both ends and 12 cm from the top.
- 1320 Hz, (3, 0) mode: There seem to be three nodes near 3, 15, and 24 cm, although the separation (resolution) is poor near both edges because of small numbers of microphones. The frequency ratio of 1320 Hz to 483 Hz is 2.733. This value is very close to 2.758 for the free-free rod vibration.

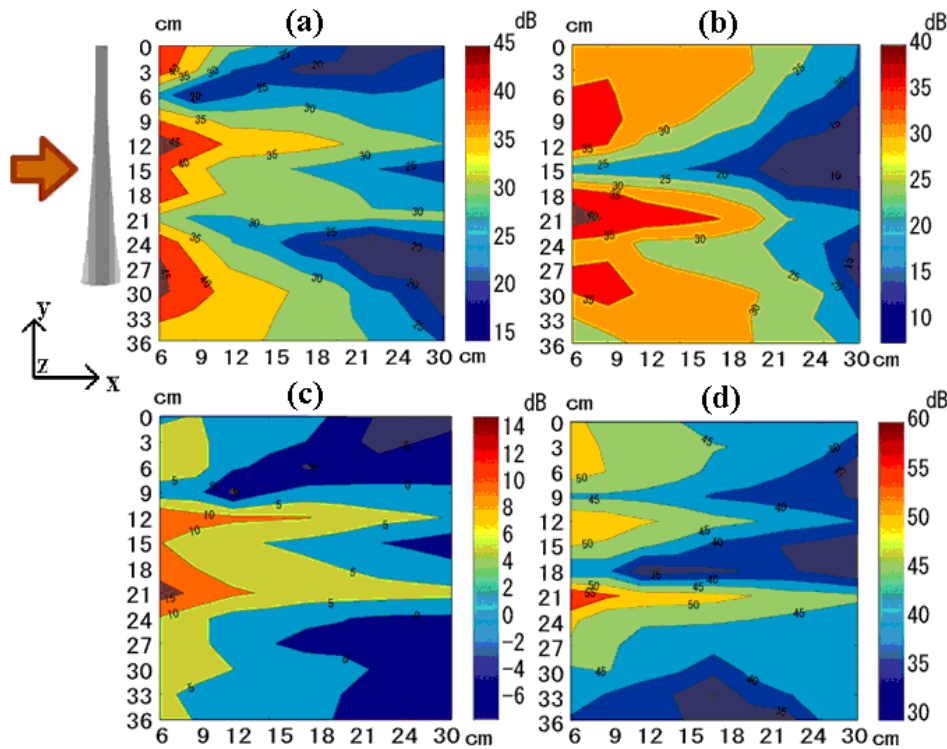


Fig. 15. Lateral radiation field of a miniature Gaudí bell. (a): 483 Hz; (b): 1320 Hz; (c): 1672 Hz; (d): 2412 Hz.

- (c) 1672 Hz, (4, 0) mode: the node positions might be estimated near 3, 9, 15, and 27 cm. The radiation of this (4, 0) mode is significantly weaker than that of (3, 0) mode. This may be because the node near 15 cm in (3, 0) mode suppresses the loops around 15 cm in (4, 0) mode. This explanation may be applicable to (2, 0) mode. The frequency ratio of 3.462 is much smaller than 5.406 for the free-free rod.
- (d) 2412 Hz, (5, 0) mode: Two nodes near 9 and 18 cm are clear, but the resolution is too low to separate five nodes from each other.

The lateral directivity pattern (measured by a vertical line array) and the radial directivity pattern (measured by a semi-circular array) show a fairly good agreement with those simulated by the FE and BE methods [Horimoto et al., 2006].

The pitch sensation of the strike note for our Gaudí bell seems to be the lowest frequency of (2, 0) mode. This is identified as the “spectral pitch” [Terhardt and Seewann, 1984]. However, simple tubular bells (the wind chime made of aluminum) tuned $G_5 = 781$ Hz give the pitch as the spectral pitch determined by the (4, 1) mode [Yoshikawa, 2005]. The pitch of the strike note is a complicated problem.

CONCLUSIONS

Some suggestions may be derived from our joint research. (1) The relative position between the louvered window and the acoustic center of the bell is important to the outward radiation toward the people on the ground. (2) The attenuation of the bell sound is roughly estimated as 40 dB when heard in the nave. (3) Very-low-pitched bells are probably useless due to the cutoff frequency (at around 100 Hz) of the lower structure. (4) The reverberation in the nave might be reduced by scattering sounds caused by the floor reflection. The acoustical research on the Sagrada Família Church and Gaudí’s bells should be much developed in the future.

ACKNOWLEDGMENTS

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